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Using instantaneous cross-correlation coefficients of vibration signals for technical condition monitoring in rotating electric power machines

Proposed in the article is the use of new high-information characteristics, in which capacity we used cross-correlation coefficients between vibration signals in space-distributed units of a rotating electric machine in combination with amplitudes of vibration signals in the same units. It was theoretically proven that the said characteristics make it possible to restore the information on the amplitudes and spatial localizations of occasional uncompensated disturbing forces, the influence of which gives rise to vibrations during rotating electric machines' operation. Determined and theoretically substantiated was the duration of vibration signal's temporal realizations, which is advisable to use when obtaining vibration signals' cross-correlation coefficients in the units under investigation. It was found that duration of such realizations must be divisible by the frequency of rotation period of electric machine's rotor. Besides, adapted was the mathematical model for calculation of cross-correlation coefficients taking into account the specificities of origin and the physical nature of vibration signal, which enabled us, having significantly simplified the analytical calculations required for obtaining the cross-correlation coefficients, to calculate cross-correlation coefficients based on measured values of their temporal realizations directly in the real-time mode of electric power machine's operation. The adequacy of the statements set forth in the article and the informative value of proposed characteristics were proven by way of computerized simulation.

Keywords: measurement, cross-correlation, rotating electric machine, system's vibration response, cross-correlation coefficient, uncompensated disturbing force.

Introduction

An important task arising during operation of electric power machines, including hydraulic units of HPPs (hydropower plants) and PSEPPs (pumped-storage electric power plants), consists in ensuring maximum reliability and duration of equipment operation with minimum costs of maintenance thereof. And since the classical approach to ensuring reliable operation of equipment provides for identification of possible defects during equipment shutdown and for performance of scheduled repairs, which is far from always technically substantiated, apparent is the necessity to develop new approaches that would allow optimizing the operational costs and increasing the period of equipment operation between scheduled repairs.

In view of the foregoing, development of methods for indirect monitoring of technical condition of electric power equipment in the real-time mode of its operation becomes increasingly relevant [1-3]. However, the use of such approaches is currently limited by the absence of not only explicit mathematical models, but also of high-information characteristics, the analysis of which would make it possible to identify changes in basic technical parameters of rotating power machines to a high degree of accuracy [3]. Hence, identification of informative characteristics that would, on the one part, correlate well with technical parameters of a rotating electric machine, and on the other part – would enable performing their high-precision measurement in the real-time mode of the technological process, is a crucial scientific-and-application task, the solution of which is of a significant interest both in theoretical and in practical terms.

Setting the task

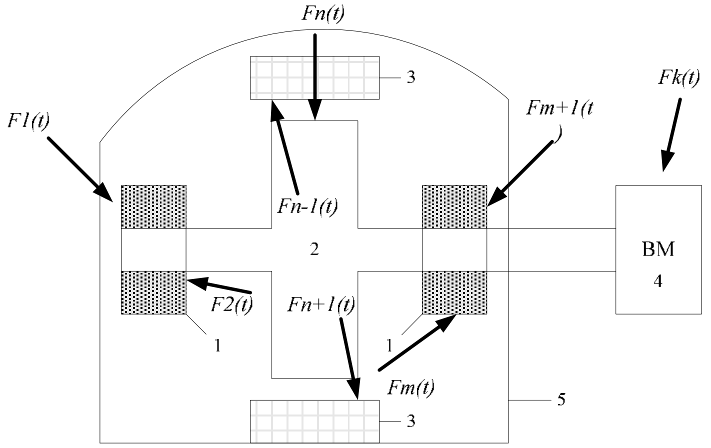
As it was shown in papers [1-4], the systems for control of technical condition based on analysis of unit assemblies' vibration signals are highly promising in terms of solving the technical task assigned. However, the overwhelming majority of working hypotheses, based on which the methods for technical condition monitoring are based, consider the units of a rotating power machine separately, analyzing the obtained results, at the best, statistically only in an upper-level numeric converter [3, 4]. Such approach makes it impossible to evaluate the degree of disturbances' localization and the degree of their influence on the entire space-distributed structure of an electric machine. As a consequence, based on the measurement information obtained, it is impossible neither to imagine the geometrical location of the point of application of equivalent uncompensated force that causes vibration (which indirectly testifies to the reason of its origin), nor to make conclusions regarding the mechanical stiffness of the electrical machine's support structure (which is the parameter directly connected with mechanical strength). And if the problem of identifying the reason behind increasing vibration is in a number of papers [3, 5, 6] proposed to be solved based on spectral analysis of a vibration signal using the fuzzy-set theory, the problem of monitoring the mechanical stiffness in the real-time mode is totally disregarded by the existing approaches.

It is worth noting that identifying the reasons behind vibration increase based on vibration signal's spectral analysis only will also result in obtaining quite disputable conclusions, since vibration frequency itself is only an indirect factor, while uncompensated external disturbances of various nature that give rise to vibration increase may manifest themselves in the same frequency domains [3]. Another factor that limits the use of spectral analysis for a local unit in its pure form lies in availability of own resonant frequencies of structural elements' local units, where influences of particular disturbances may be increased significantly, and presence of a complicated interference picture of vibration within the elastic environment of electric machine structures [7] that may considerably distort the vibration signals conditioned by the action of local influential values. Hence, in view of the foregoing, evident is the necessity to develop new and more efficient methods for analysis of rotating machines' technical condition that requires solution of two applied scientific tasks, and namely: identification of a high-information criterion that would characterize the vibration condition of the entire monitored object (MO) and correlate well with its basic technical parameters and establishing functional connections between this criterion and technical parameters of an electric machine. The objective set in this paper lies in solution of the first formulated applied scientific task by way of identification and theoretical substantiation of using a high-information criterion that could be measured in the real-time mode of the technological process, that would contain the information on both amplitude and spatial localization of external disturbing influences, and on the mechanical stiffness of MO structure. At the same time, solution of this task will be of both theoretical and practical interest.

Analysis of approaches to the task solution

Considering a rotating electric machine as a MO, one can imagine it as a relatively stationary distributed quasi-linearized inseparable elastic system having spatially variable coefficients of stiffness [8]. Another specific feature of MO lies in its being exposed to k spatially distributed uncompensated mechanical forces of various nature, amplitude and vector direction to change in a temporal function randomly. The structure of such MO may more simply be presented as follows (Fig. 1).

In view of such system's non-separability, any of k external uncompensated disturbing forces will generate, in the system's randomly selected point (node), some vibration signal (response), the amplitude of which being other than zero [9]. That said, taking into account the system's stationary state, vector-identical force, the equivalent of which is applied to the electrical machine's one and the same point, will give rise to the system's identical response in any randomly selected assembly of the unit. Taking into account the foregoing, for a randomly selected controlled unit in relation to each of k possible disturbing forces, one can select a transient characteristic that will possess a relatively time-constant value on account of a high inertia of the process of change in the mechanical stiffness of the electric machine's units under acceptable operational conditions.



1 – bearings; 2 – rotor; 3 – stator; 4 – actuating mechanism; 5 – outer case

Figure 1. Simplified flow diagram of a rotating electric machine:

In other words, for a randomly selected unit A being a part of the MO, the following system will be true:

$$\begin{cases} \psi_{A1}(t) = F_1(t)\cdot H_{A1}(t), \\ \psi_{A2}(t) = F_2(t)\cdot H_{A2}(t), \\ \dots\dots\dots\dots\dots\dots \\ \psi_{Ak}(t) = F_k(t)\cdot H_{Ak}(t), \end{cases} \tag{1}$$

where $F_1(t)$ – $F_k(t)$ – the uncompensated forces affecting the electric machine; $H_{A1}(t)$ – $H_{Ak}(t)$ – transient characteristics in relation to disturbing forces $F_1(t)$ – $F_k(t)$, respectively; $\psi_{A1}(t)$ –$\psi_{Ak}(t)$ – the system's response at A point to the effect of disturbance in the form of $F_1(t)$ – $F_k(t)$ force, respectively.

Such being the case, the resultant vibration signal to be observed at A point may be obtained based on the superposition principle.

$$\psi_A(t) = \sum_{i=1}^{k}\psi_{Ai}(t) = \sum_{i=1}^{k}F_i(t)\cdot H_{Ai}(t). \tag{2}$$

Proceeding from similar reasoning, the described mathematical apparatus may be extended to any other random point B, which also belongs to MO and does not coincide with point A. Such being the case, for point B, dependence of vibration signal's response on disturbing forces will be written as follows:

$$\begin{cases} \psi_{B1}(t) = F_1(t)\cdot H_{B1}(t), \\ \psi_{B2}(t) = F_2(t)\cdot H_{B2}(t), \\ \dots\dots\dots\dots\dots\dots \\ \psi_{Bk}(t) = F_k(t)\cdot H_{Bk}(t), \end{cases} \tag{3}$$

$$\psi_B(t) = \sum_{i=1}^{k}\psi_{Bi}(t) = \sum_{i=1}^{k}F_i(t)\cdot H_{Bi}(t). \tag{4}$$

Taking into consideration (1) and (3),and the fact that MO is a quasilinear system, the dependence of the system's each response at point B on the system's response at point A will be written as follows:

$$\psi_{Bi}(t) = \frac{H_{Bi}(t)}{H_{Ai}(t)}\psi_{Ai}(t). \tag{5}$$

Hence, the system's general response at B point may be determined as

$$\psi_B(t) = \sum_{i=1}^{k}\frac{H_{Bi}(t)}{H_{Ai}(t)}\psi_{Ai}(t). \tag{6}$$

Other points belonging to MO may similarly be connected between each other.

Though expression (6) theoretically makes it possible to establish an unambiguous connection between vibration signal's functions in different MO parts, which could ensure the possibility, based on known implementations of vibration signal in the said points, to restore the contribution by each of $F_i(t)$forces for each time moment under investigation, however for a real rotating electric machine it is practically impossible to determine not only particular points for application of equivalent disturbing forces, but even to obtain reliable information on their precise number [3, 4, 10]. Therefore, the use of (6) in its pure form is quite restricted. However, in order to determine the type of disturbing effect during operation of real rotating electric machine, it sometimes will be quite sufficient to approximately determine the local area for application of predominant disturbance, which significantly facilitates the solution of the task set.

Taking into account the foregoing and the fact that, due to the stochastic nature of disturbing uncompensated forces $F_1(t) – F_k(t)$, the analyzed MO may be deemed a stochasticsystem, expression (6) will essentially transform into theoretical substantiation of availability of cross-correlation connections between vibration signal's responses in different points of the electrical machine under investigation. Besides, in view of the fact that stiffness coefficient of MO structures around any its point exceeds zero [7], it is evident that the value of cross-correlation coefficient between vibration signals in the units under investigation will grow with approximation of the point of application of external disturbance's significant component to the conditional point of mechanical center between them, and will be proportionate to this disturbing force's relative contribution to formation of the general vibration signal. Furthermore, evident is the statement that vibration signal's amplitude in some particular unit will be proportionate both to the conditional mechanical distance to the points of application of significant disturbing forces and to their absolute amplitude. Hence, one can deem entirely proven the hypothesis claiming that the use vibration signals' cross-correlation coefficients between spatially separated MO units together with their instantaneous amplitudes will allow obtaining the data package containing the information not only on the amplitude of disturbing influences, but also on their spatial localization that may be associated with the reasons of their origin to a high degree of probability.

Obtaining instantaneous values of cross-correlation coefficients is a considerable challenge for the use of the approach proposed. As was shown above, since vibration processes in electrical machine's controlled units are of random nature, precise evaluation of linear connection between the two values $\psi_A(t)$ and $\psi_B(t)$ would require the use of the following expression [9]

$$K_\psi(t_1,t_2)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(\psi_1-m_A(t_1))(\psi_2-m_B(t_2))\cdot f(\psi_1,\psi_2,t_1,t_2)\,d\psi_1 d\psi_2, \tag{7}$$

where m A(t1), mB(t2) – mathematical expectations of ψA(t) and ψB(t) functions in t1 and t2. time moments, respectively; $f(\psi_1,\psi_2,t_1,t_2)$ – two-dimensional density probability of an occasional process ψ(t) that preconditions the appearance of vibration signals in A and B units that is determined at t1 and t2 time moments, in relation to which occasional process ψ(t) may be considered as the system of two random values ψA(t) and ψB(t), the values ψ1 and ψ2 of which being ψA(t1) and ψB(t2) values of occasional process realizations recordedat t_1 and t_2 time moments.

$$f(\psi_1,\psi_2,t_1,t_2)=\frac{\partial^2 F(\psi_1,\psi_2,t_1,t_2)}{\partial\psi_1\partial\psi_2}, \tag{8}$$

where $F(\psi_1,\psi_2,t_1,t_2)$ – two-dimensional function of distribution of occasional process probabilities $\psi(t)$ that assigns the value of probability of the fact that at t_1 time moment $\psi_A \le \psi_1$ in equation is implemented, and at t_2 time moment $\psi_B \le \psi_2$ in equation is implemented, that is

$$F(\psi_1,\psi_2,t_1,t_2)=P(\psi_A(t_1)\le\psi_1,\psi_B(t_2)\le\psi_2). \tag{9}$$

Let us adapt the mathematical apparatus (7) – (9) to the MO under investigation. As was shown above, the disturbing forces $F_1(t) – F_k(t)$ are distributed along the MO in such a way that points of application of their equivalents may be located at different conditional mechanical distances from A and B units. In this case, for some forces conditional mechanical distance from the point of application of the equivalent to unit A will exceed the conditional mechanical distance to unit B, for others – be equal, and for some others – be less. Hence, the rate of propagation of mechanical disturbance for each of k forces to controlled units will be different, which precludes from speaking about availability of time delay between system responses in the said points. Consequently, taking into account the specificity of MO, the autocorrelation coefficient between$\psi_A(t)$ and $\psi_B(t)$ signals will be advisable to determine for one and the same time moment, that is

$$t_1=t_2. \tag{10}$$

This results in thecross-correlation coefficient $K_\psi(t_1,t_2)$ transforming into $K_\psi(t_1)$.

Considering the vibration signal at stationary disturbing external influences $F_1(t) – F_k(t)$, which in physical terms will correspond to permanent qualitative composition and stationarity of laws of amplitude variation in uncompensated forces $F_1(t) - F_k(t)$, signals $\psi_A(t)$ and $\psi_B(t)$ may be considered ergodic. Such being the case, cross-correlation coefficient $K_\psi(t_1)$ of stationary occasional process $\psi(t)$ may with a slight error be considered equal to cross-correlation coefficient of certain temporal realization of $\psi_A(t)$ and $\psi_B(t)$ signals, for which the ergodic property will be implemented. In view of the fact that disturbing forces $F_1(t) - F_k(t)$ may only be deemed stationary during quite a short time period, while the value of vibration signal remains functionally dependent on angular position of electric machine's rotor [11, 12], in such case most admissible being the duration of realization of time series of $\psi_A(t)$ and $\psi_B(t)$ functions, which coincides with duration of rotation period of electric machine's rotor (for high-speed machines this may be divisible by period under acceptable value of duration). As a result, it would be entirely advisable and substantiated to proceed from calculation of instantaneous cross-correlation coefficients to calculation of quasiinstantaneous coefficients bound to the specified duration of temporal realization of $\psi_A(t)$ and $\psi_B(t)$ functions. On this basis, the unknown quasi-instantaneous cross-correlation coefficient may be calculated as follows:

$$K^*_\psi(t_1) = \frac{1}{T}\int_0^T (\psi^*_A(t_1) - m_A(t_1))(\psi^*_B(t_1) - m_B(t_1))dt_1, \tag{11}$$

where T – duration of temporal realization of $\psi_A(t)$ and $\psi_B(t)$ functions; $\psi^*_A(t)$ and $\psi^*_B(t)$ – temporal realizations of $\psi_A(t)$ and $\psi_B(t)$ functions.

And since oscillations of any elastic body occur in relation of some central (zero) position, then in the time period divisible by a rotation period of electric machine's rotor, a vibration signal of its any unit may be considered centered. Such being the case, the expression for calculation of cross-correlation coefficient between vibration signals of two distributed units will be written as follows:

$$K^*_\psi(t_1) = \frac{1}{T}\int_0^T (\psi^*_A(t_1))(\psi^*_B(t_1))dt_1. \tag{12}$$

Since the measurement of output vibration signals in real monitoring systems is frequently performed in a discrete way, then for discrete temporal realizations, taking into account the well-known Pearson equation (12) can be written as follows:

$$K^*_\psi(t_1) = \frac{\sum_{i=1}^{n}\psi^*_{Ai}\psi^*_{Bi}}{\sqrt{\sum_{i=1}^{n}\psi^{*2}_{Ai}\cdot\sum_{i=1}^{n}\psi^{*2}_{Bi}}}, \tag{13}$$

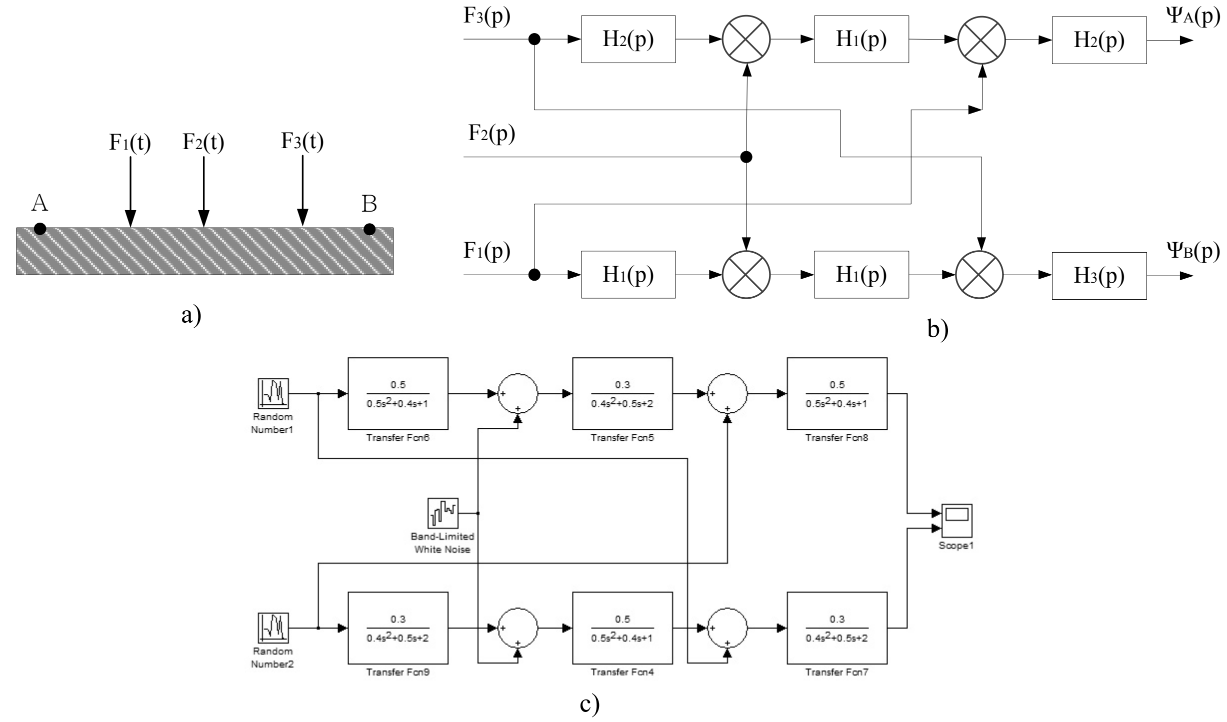
where ψ^*_{Ai} and ψ^*_{Bi} – i-th values of temporal realizations of $\psi_A(t)$ and $\psi_B(t)$ functions.

The above-stated hypothesis about availability of correlation dependences in output vibration signals of spatially distributed MO points and their dependence on spatial localization of significant disturbing forces may be confirmed by way of computerized simulation. Such being the case, it would be quite sufficient to evaluate cross-correlation connections of output signals of an elastically attached system subjected to uncompensated disturbance by three spatially-distributed non-correlated forces, since if the statements are deemed true in the case under investigation, these could also be expanded to other more complicated cases. It would be advisable to select the geometrical location of the points of application of equivalent forces in such a way that one of them could be located in a conditional mechanical center between controlled points A and B, with two others displaced to different conditional mechanical distances toward the first and the second controlled points, respectively. The initial provision that would be worth considering when generating an adequate computer model is as follows: under normal operational conditions, electrical machine's structures are largely affected by elastic deformation [4] that enables representing the elastic connection between spatially distributed MO units in P-plane in the form of oscillatory links of the following type [7]:

$$H(p) = \frac{k}{T_1p^2 + T_2p + 1}, \tag{14}$$

where k – amplification coefficient (for an actual physical system being less than k<1); T_1, T_2 – time constants of an oscillatory link.

Besides, when generating a computer model one should take into account that, for the considered case of aquasi-linear system, its multi weight components, spatially located between the system's inputs and outputs, may be represented in the form of one equivalent link with a transmission characteristic of (14) [8] type. Such alteration does significantly simplify the structure of a computer model. Another simplification that will not have any significant influence on the model's adequacy, however significantly allowing the building thereof, is the MO representation as a system with one-dimension elastic connections, since in the case of adequacy of the theoretical conclusions made for such a MO, these can be quite easily extended to three-dimensional MO. An additional problem to be solved when generating the model lies in the choice of magnification coefficients, time constants and dispersion of disturbing forces. However, taking into account the system's specificity, cross-correlation connections therein will be preserved with a proportionate increase of all time constants or magnification coefficients [8]. Hence, lacking the information on the values of the said parameters, let us restrict ourselves with their random choice while preserving one order of values for all blocks of the model generated. In view of the foregoing, the flow diagram and the mathematical model of MO with the specified simplifications may be represented in the form shown in Figure 2.



a) – flow diagram, b) – structure of mathematical model of simplified MO in P-plane,
c) – model of simplified MO using MATLAB Simulink means

Figure 2. Simplified simulated monitoring object:

Since the system's input signals are represented by stochastic values, the results is represented by averaged values of cross-correlation coefficients obtained as the arithmetic average value of cross-correlation coefficient among ten signal realizations at the computer model's outputs for each of disturbance conditions under investigation, respectively. Obtained results are set forth in Table.

Table

Computerized Simulation Results

Simulation conditions	Averaged cross-correlation coefficient
$F_1(t) \approx F_2(t) \approx F_3(t)$ (All disturbing forces being one amplitude order)	0.278
$F_1(t) >> F_2(t) \approx F_3(t)$ ($F_1(t)$ amplitude is by one order higher than $F_2(t)$ and $F_3(t)$ amplitude)	0.18
$F_1(t) \approx F_3(t) << F_2(t)$, ($F_2(t)$ amplitude is by one order higher than $F_1(t)$ and $F_3(t)$ amplitude)	0.54
$F_1(t) \approx F_2(t) << F_3(t)$ ($F_3(t)$ amplitude is by one order higher than $F_1(t)$ and $F_2(t)$ amplitude)	0.11

As you can see from the results presented in Table, simulation results do entirely confirm the hypotheses set forth above. Hence, one can state that cross-correlation coefficients obtained in (12) or (13), together with absolute amplitudes of temporal realizations' vibration signals, will contain information on both the amplitudes and spatial localization of disturbing forces and on the mechanical stiffness of rotating electric machine's units in an implicit form, the informative value of which will grow with the increase in the quantity of unit couples, for which we will obtain the cross-correlation coefficient and the number of units, for which the value of absolute amplitude temporal realizations of the vibration signal will be known. Hence, as the method for increase of information value and accuracy of MO parameters control, one can propose an approach that provides for a parallel measurement of vibration signals in spatially distributed points of a rotating electric machine, the number of which must be determined by a sufficient probability for determination of an equivalent amplitude of uncompensated disturbing forces $F_1(t) – F_k(t)$ and sufficient spatial localization of the point of application of each significant equivalent of these forces. Such being the case, the monitoring system based on the use of cross-correlation coefficient swill require an additional channel for the rotor's angular position necessary for determination of actual duration of vibration signals' temporal realizations.

Conclusions

1. Proposed was the use of new high-information characteristics containing the information on not only the amplitude and spatial localizations of uncompensated disturbing forces(directly connected with the reasons of their origin), the influence of which gives rise to vibrations during operation of rotating electric machines. Theoretically proven and substantiated was the appropriateness of their functional connection and the advisability of use.
2. Determined and theoretically substantiated was the duration of vibration signal's temporal realizations, which is advisable to use when obtaining vibration signals' cross-correlation coefficients in the units under investigation. It was established thatduration of such realizations must be divisible by the frequency of rotation period of electric machine's rotor.
3. Adapted was the mathematical model for calculation of cross-correlation coefficients, taking into account the specific features of vibration signal's origin and physical nature, which allowed significantly to simplify the analytical calculations required for obtaining the cross-correlation coefficients.

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Электрлік айналмалы машиналардың техникалық жағдайын бақылау мониторингі үшін дабыл дірілдерінің өзара корреляциясының мезеттік коэффициенттерін қолдану

Мақалада айналмалы электрлік машинасының кеңістікте үлестірілген нүктелерде дірілді дабылдардың амплитудаларына сәйкесті дірілдер аралығында өзара корреляция коэффициенттері қолданылған жаңа жоғары ақпаратты сипаттар ұсынылды. Көрсетілген сипаттамалар айналмалы электрлік машиналардың жұмысы кезінде дірілді қалыптастыратын кездейсоқ қоздырушы күштерді кеңістіктік шектеу және амплитуда жайлы ақпаратты қалпына келтіруге мүмкіндік беретіні теориялық тұрғыда дәлелденді. Зерттелетін нүктелерде діріл дабылдарының өзара корреляция коэффициенттерін алу кезінде қолданатын дірілдердің қалыптасуының мезеттік ұзақтығы анықталды және теориялық түрде негізделді. Мұндай қалыптасулардың ұзақтығы электрлік машинаның роторы айналуы периодының жиілігіне еселенген болуы керектігі тағайындалды. Сондай-ақ дірілдің шығу тегі мен физикалық сипатын ескере отырып, корреляциялық коэффициенттерді есептеудің математикалық моделі қабылданды, бұл өзара қатынас коэффициенттерін алу үшін қажетті аналитикалық есептеулерді едәуір жеңілдетуге және олардың уақытша іске асырылған өлшенген мәндеріне негізделген күштік электр машинасының нақты уақыт режимінде тікелей корреляциялық коэффициенттерін есептеуге мүмкіндік берді. Мақалада келтірілген мәлімдемелердің және ұсынылған мүмкіндіктердің ақпараттық мазмұнының жеткіліктілігі компьютерлік модельдеу арқылы дәлелденді.

Кілт сөздер: өлшеу, өзара корреляция, айналмалы электрлік машинасы, жүйенің дірілі реакциясы, өзара корреляция коэффициенті, компенсирленбеген қоздырушы күш.

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Использование мгновенных коэффициентов взаимной корреляции сигналов вибрации для мониторинга технического состояния вращающихся электрических машин

В статье представлены новые высокоинформационные характеристики, в которых использовали коэффициенты взаимной корреляции между вибрационными сигналами в пространственно-распределенных точках вращающейся электрической машины в сочетании с амплитудами вибрационных сигналов в тех же точках. Теоретически доказано, что эти характеристики позволяют восстановить информацию об амплитудах и пространственных локализациях случайных нескомпенсированных возмущающих сил, влияние которых вызывает колебания при работе вращающихся электрических машин. Определена и теоретически обоснована продолжительность временных реализаций вибрации, которые целесообразно использовать при получении коэффициентов взаимокорреляции вибросигналов в исследуемых точках. Установлено, что продолжительность таких реализаций должна быть кратная частоте периода вращения ротора электрической машины. Кроме того, адаптирована математическая модель для расчета коэффициентов взаимной корреляции с учетом особенностей происхождения и физической природы вибрационного сигнала, что позволило значительно упростить аналитические вычисления, необходимые для получения коэффициентов взаимной корреляции, для расчета коэффициентов взаимной корреляции на основе измеренных значений их временных реализаций непосредственно в режиме реального времени работы электрической машины. Изложенные в статье предлагаемые характеристики были доказаны с помощью компьютеризированного моделирования.

Ключевые слова: измерение, взаимная корреляция, вращающаяся электрическая машина, реакция вибрации системы, коэффициент взаимной корреляции, нескомпенсированная возмущающая сила.

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